Thesis for the degree of Licentiate of Engineering

Behaviour and material properties of composites for crash modelling

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Göteborg, Sweden 2016

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Licentiatavhandlingar vid Chalmers tekniska högskola
Technical report No. 2016:09
ISSN 1652-8565

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Cover: Composite crashbox (Photo by Thomas Bru)

Printed by Chalmers Reproservice
Göteborg, Sweden 2016

Abstract

The transport industry must find solutions to reduce its impact on climate change. A promising way to reduce the weight of vehicles and therefore to reduce the CO_2 emissions is to introduce components made of lightweight composite materials, in particular laminated carbon fibre reinforced polymers (CFRPs). Aside from the new design possibilities for lighter vehicle structures, CFRPs can also potentially offer large improvements in terms of energy absorption capabilities in comparison to traditional crash components made of metals.

During crushing of composites, a large amount of energy is absorbed through stable progressive failure of the material. The crushing process is a complex phenomenon because it is driven by the combination of many failure mechanisms and frictional effects. A limited amount of research has been performed on crushing of composites, mainly because crashworthiness is not a critical requirement in the aerospace industry (the predominant market for advanced composites today). As a result, there is today no reliable numerical tool to predict the crashworthiness of CFRP structures, which is a hindrance to the introduction of composite materials in mass-produced automobiles. Joint research efforts from both numerical and experimental perspectives are needed to fill this void and reach the goal of reliable crash predictions of composite vehicles.

The focus of this thesis is on a material characterisation strategy for crash modelling of composites. An experimental methodology is developed to provide relevant and accurate input to a physically-based material model for crash, currently being developed in parallel to this thesis.

The material selected for this research is a CFRP with non-crimp fabric (NCF) reinforcements. The first step in the material characterisation is to extract the different strengths and stiffnesses of the material, which requires dedicated tests because of the orthotropic nature of NCF composites. In a second step, more specific inputs to ply damage models for progressive failure are extracted from experiments. Those parameters are (1) damage evolution laws, identified from Iosipescu shear tests, and (2) the longitudinal and the transverse crushing behaviour of unidirectional laminates, extracted from relatively simple crush tests on flat specimens.

Keywords: carbon fibre composite, non-crimp fabric, crushing, mechanical testing.

Acknowledgments

The research presented in this thesis was carried out at Swerea SICOMP in Mölndal and at the department of Applied Mechanics at Chalmers University of Technology in Göteborg. This project is funded by the Swedish Energy Agency (Energimyndigheten) 34181-1, whose financial support is gratefully acknowledged.

I would like to express my gratitude to several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this licentiate thesis.

First and foremost, my supervisors Prof. Robin Olsson and Dr. Gaurav Vyas. Robin has supported me throughout my work with his patience and invaluable knowledge. Gaurav's good advice, support and friendship have also been of great help;

My colleagues at Swerea SICOMP for guiding me in my work and helping me in developing my skills as a researcher;

The composite team from Applied Mechanics at Chalmers. Our regular meetings is always a good opportunity to share our knowledge and help each other, for which I am extremely grateful;

My familly and my girlfriend Josefin, for the support they give me every day.

Thomas Bru

Göteborg, May 2016

List of Publications

This thesis is based on the following appended papers:

Paper A. Thomas Bru, Peter Hellström, Renaud Gutkin, Dimitra Ramantani and Göran Peterson. Characterisation of the mechanical and fracture properties of a uni-weave carbon fibre/epoxy non-crimp fabric composite. *Data in Brief* 6, 680–695 (2016).

Paper B. Thomas Bru, Robin Olsson, Renaud Gutkin and Gaurav M Vyas. In-plane and through-the-thickness shear testing of composites with Iosipescu specimens: experiments and simulations. (Ready for submission)

Paper C. Thomas Bru, Paul Waldenström, Renaud Gutkin, Robin Olsson and Gaurav M Vyas. Investigation of the longitudinal and transverse crushing behaviour of unidirectional flat specimens. (Under review; May 2016)

The three appended papers were prepared in collabaration with the co-authors.

In Paper A the author was responsible for coordinating the test campaign, and writing of the paper. The author was also responsible for the through-the-thickness tests and the shear tests. The other tests were performed by the co-authors and the results reported internally at Swerea SICOMP and Volvo GTT.

In Paper B the author was responsible for the major progress of the work, including the design of the tests, the post-processing of the results, the failure analyses, performing the simulations and writing of the paper, all with assistance from the co-authors.

In Paper C the author was assisting Paul Waldenström in the design of the test and the manufacturing of the specimens, the testing and the post-processing of the results and the failure analyses. The author wrote most of the paper with assistance from the co-authors.

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Part I

Extended summary

1 Introduction

1.1 Composite materials

Today advanced composite materials are widely used in aircraft structures, racing cars, boat hulls, sport goods and other components designed for high stiffness and strength at low weight. For those applications, the aim is to increase the performance by using the best engineered composite materials. In terms of specific mechanical properties, continuous fibre reinforced polymers (FRPs), and especially carbon fibre reinforced polymers (CFRPs), are ranked top amongst advanced composites. They offer outstanding performance compared to other classes of materials like pure plastics and pure metals. On the Airbus A350 XWB and Boeing 787 Dreamliner commercial aircraft, more than half the airframe is made from CFRPs, which allows considerable weight savings compared to a metallic airframe.

FRPs are made from fibres that are embedded into a matrix (or resin) material. The mechanical function of the matrix is to transfer the load between the fibres. Typical resins in FRPs are thermoset plastics (e.g. epoxies) and thermoplastics (e.g. polyamides). Prepreg and textile reinforcements are the two types of reinforcements that can be considered for continuous FRPs. Prepreg reinforcements are commonly unidirectional (UD) tapes, in which the fibres which have been pre-impregnated with the resin system. Textile reinforcements include woven, braided, knitted, and non-crimp fabric (NCF) reinforcements. Photographs of a prepreg and a textile reinforcement are shown is Fig. 1.

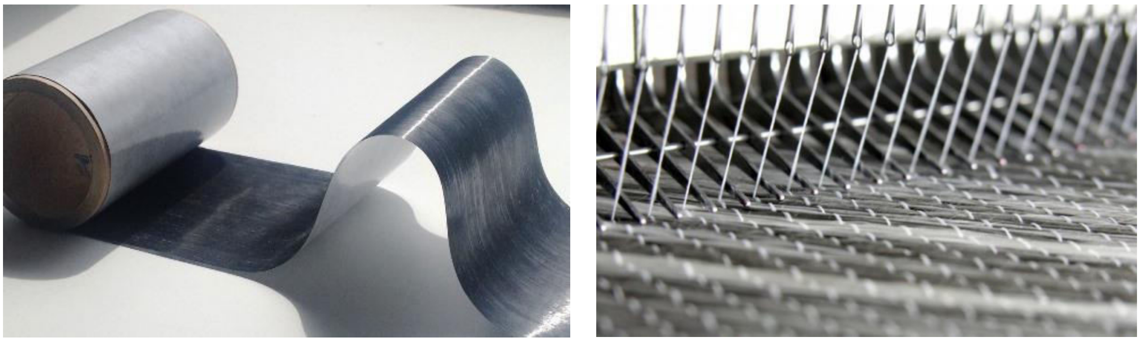

Figure 1: Two types of reinforcement for continuous FRPs. Left: A prepreg tape [1]. Right: A textile NCF shown during its manufacturing [2].

Regardless of the choice of reinforcements, continuous fibre reinforced laminates are obtained by stacking layers (also called lamina, or plies) of different fibre orientations on top of each other. The stacking sequence and number of layers depends on the desired mechanical properties for the final product.

1.2 Towards composite road vehicles

The road transport industry, which contributes to about one-fifth of the total CO_2 emissions, must find solutions to reduce its impact on climate change. It is legislated that by 2020 the car fleet of European car manufacturers should not emit more than an average of 95 grams of CO_2 per kilometre [3]. Studies have shown that the weight reduction of road vehicles can play an important role in the attainment of the requirements of the future legislation. For every 10% passenger car weight reduction, the fuel economy improves by 5 to 7%, and for every kilogram of passenger car weight reduction, the potential reduction of CO_2 emissions is about 20 kg [4].

Structural components make up to nearly half of the weight of passenger cars. Currently they are made of advanced steels, aluminium and other metallic materials. Those materials have higher density than composites and offer limited possibilities in the redesign of cars, busses, and trucks. Lightweight composite materials must be used to reach important structural weight savings. Recently, BMW led the automotive industry into the use of CFRPs. The BMW i3, which began mass production in 2013, pioneers the use of a composite roof and other parts reinforced with recycled carbon fibre [5].

Composites reinforced with prepregs are used extensively in the aerospace industry, despite their high material costs and slow manufacturing process (autoclave process). The automotive industry has historically been driven by cost. In the automotive industry, the manufacturing has to be much faster than that of aircraft to achieve the required production volume. Therefore, alternatives to prepreg reinforcement must be considered for composite vehicle manufacturing to be cost-effective.

1.3 Crashworthiness

A critical requirement for the transport industry is crashworthiness. The crashworthiness of a vehicle describes its ability to absorb kinetic energy in the event of a crash in a controlled manner such that the vehicle will decelerate at a rate that limits the load transmitted to the occupants. The crashworthiness requirement can be fulfilled by employing energy absorption components in the crush zones of the vehicle (e.g. front and rear assemblies). An energy absorption component is designed to absorb energy through progressive failure.

Crashworthiness of road vehicles is determined based on performance in crash tests. For passenger cars, a grade indicating the safety of occupants in crash events is assigned to every new model launched on the market. In Europe, car ratings are provided by Euro NCAP. The results of the crash test greatly influence consumer demand for a vehicle, encouraging safety improvements to new car design [6].

2 Performance of composites in crash situations

The initial research on crashworthiness of composites is from the late 1970s. The aim was then to identify the potential of composite energy absorption components. The structures investigated include crash boxes of road vehicles or beam subfloor structures of helicopters. It was found that the energy absorption in FRP structures was a function of many variables including fibre and matrix types, stacking sequence of the laminate, fibre volume fraction, fibre architecture, specimen and trigger geometry, and testing speed. The review by Jacob *et al.* [7], illustrates how the interaction of all those parameters complicates the measurement of the crashworthiness of composites and the understanding of how the energy is absorbed in a crash event.

Fig. 2 highlights the fact that crashworthiness of composites is not an intrinsic material property. The diagram compares the specific energy absorption (SEA) reported for crush tests, which generally consist of the compression of tubes and corrugated plates. The SEA is a measure of crashworthiness. It represents the energy absorbed per unit of mass of crushed material. It is clear from Fig. 2 that, for a similar type of FRP material, the SEA of a composite structure can vary significantly. Potentially, large improvements in terms of energy absorption capabilities can be achieved by using CFRPs rather than steel and aluminium. This opens up an opportunity for engineers to design lighter and safer crash structures. The scientific challenge is to ensure that the crushing response of a given composite structure would result in high energy absorption.

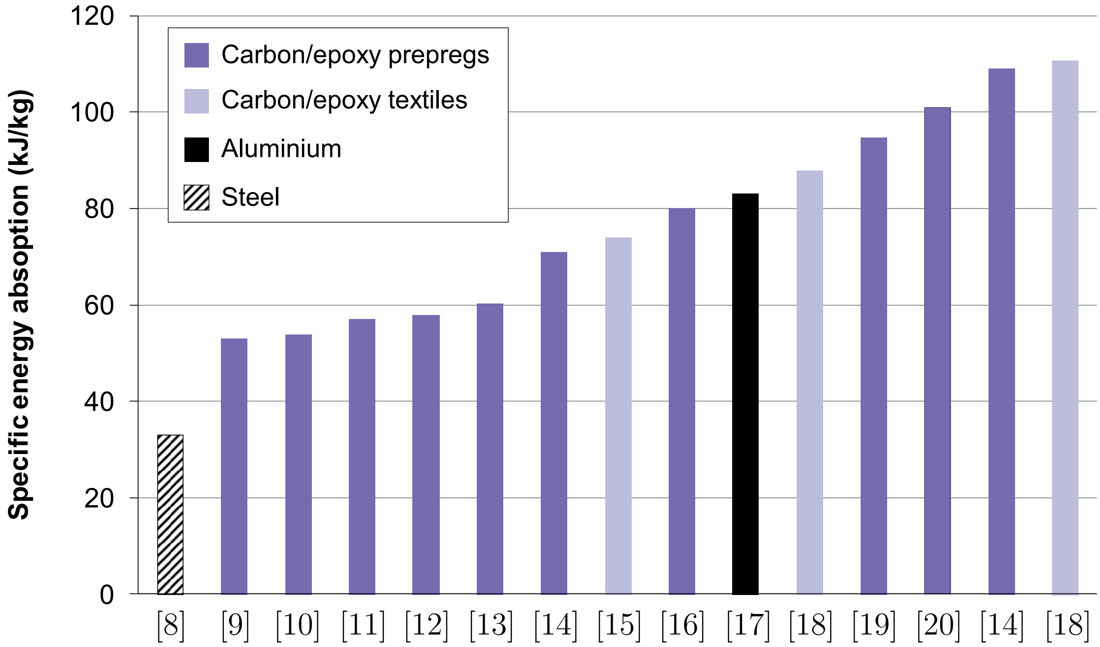

Figure 2: Comparison of the SEA of carbon/epoxy composite crash structures and metallic crash structures, with corresponding references.

2.1 Progressive failure of composite structures

Structures failing catastrophically when loaded in compression (e.g. by global buckling) do not absorb a great amount of energy. Triggering mechanisms are used in the testing of composite structures to prevent catastrophic failure and to promote stable progressive failure instead. An example of a CFRP structure experiencing stable progressive failure, i.e. crushing, is shown in Fig. 3. The energy is absorbed from the formation and propagation of cracks in the material. The friction from the contact of the fractured surfaces and the contact with the external device used for the crash test also accounts for a considerable amount of the energy absorbed.

Figure 3: Crushing of a carbon/epoxy composite tube in dynamic conditions. Courtesy of [21].

Splaying and fragmentation have been identified as the two extreme progressive failure modes of composites [14]. The two failure modes are observed simultaneously during the crushing of laminated composite structures, as shown in Fig. 3.

> *Splaying* is characterised by splayed lamina, which experience a significant amount of bending during the loading. Splaying is a result of failure at the interface between plies (*inter*laminar failure or delamination). The amount of fracture in the splayed lamina is generally small, which results in poor energy absorption capabilities. If splaying does not occur, the stresses build up in the material until fragmentation happens.

> *Fragmentation* is a progressive brittle failure mode. The laminate is partitioned into debris by multiple *inter*laminar cracks, *intra*laminar cracks (matrix cracks within a ply), and *trans*laminar cracks (fibre-breaking cracks). In contrast to splayed lamina, lamina experiencing fragmentation do not bend and are therefore carrying higher loads, which leads to a large amount of fractures and high energy absorption.

2.2 Compressive failure modes of unidirectional plies

The energy absorbing failure modes of a continuous FRP ply loaded in compression, illustrated in Fig. 4, are driven by shear.

Figure 4: Compressive failure modes of a UD ply. Left: Transverse compression. Right: Kinking failure in longitudinal compression. Courtesy of [22].

In pure transverse compression, the matrix fails in an inclined plane. The orientation of the fracture plane is not transverse to the load, suggesting that shear forces are driving the failure.

In pure longitudinal compression, failure happens by kinking or by splitting. Even if kinking ultimately results in fibre breakage, it is in fact a matrix dominated failure mode. The compressive loading of the initially misaligned fibres creates shear stresses in the matrix, which eventually fails and stops providing the sufficient support to the fibres to keep their integrity [23]. If the shear deformation in the matrix is not large enough to initiate the process of kinking, then splitting failure occurs.

2.3 Numerical predictions of the crashworthiness of composite structures

While experimental full-scale crash testing remains an integral part of safety and certification in the industry, the procedure is extremely time consuming. Because the automotive is a cost-driven industry, it must rely on the capability of finite element (FE) codes to pre-emptively simulate structural tests in order to optimise the design of crashworthy structures and to limit the number of physical tests. Unfortunately, there is today no reliable FE tool to predict the energy absorption capability of a composite structure with an arbitrary lay-up, which is a hindrance to the introduction of composite materials in mass-produced automobiles.

The great challenge presented by the simulation of composite crash structures is the complex nature of the combination of individual failure mechanisms occurring during the process of damage. There are two different modelling strategies to address the topic of crushing of composites.

Modelling strategy 1: Use of FE codes which capture the overall behaviour of the structure experiencing crushing (rather than the details of the failure mechanisms) by calibrating available material models for composites.

Modelling strategy 2: Use of FE codes which attempt to capture the detailed behaviour of the crushing phenomenon, by modelling the individual failure mechanisms occurring in the material.

In *modelling strategy 1* current material models for progressive failure of composites are used. These models are not completely physically-based, since they are based on mathematical expressions in which some parameters cannot be derived from experiments. As an example, the material model MAT54 (implemented in the commercial FE software LS-DYNA [24]) requires a total of 21 input parameters, 6 of which are numerical parameters. An iterative procedure is needed to adjust the value of the numerical parameters of the material model in order to correlate well with the experimental crushing response of composite structures [25], which make the modelling strategy not fully predictive.

Modelling strategy 2 is the strategy considered within the scope of this research. It is based on phenomenological models, i.e. physically-based models describing the physics of the crushing process. Physically-based models require relevant and accurate experimental input in order to be predictive. Keeping in mind the complexity of the crushing response of FRP structures, joint research efforts from both numerical and experimental perspectives become of tremendous importance, as illustrated in Fig. 5.

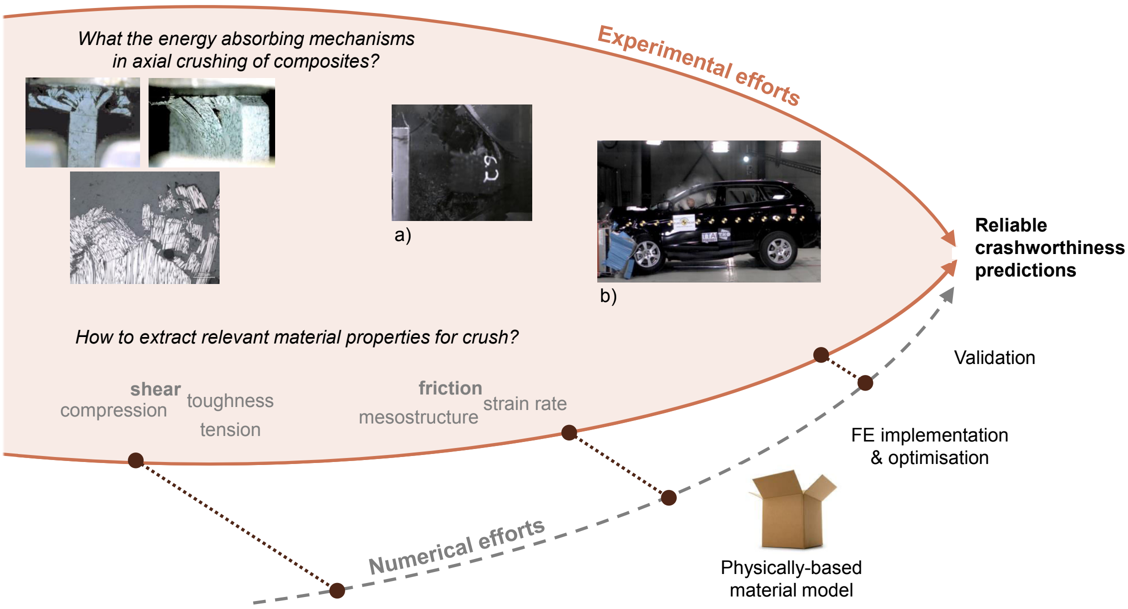

Figure 5: The experimental road map towards predictive computational models for composites in crash situation. a) Courtesy of [21]. b) © 2016 Euro NCAP [26].

The core of the experimental efforts cover several aspects:

1. The identification and understanding of the key failure mechanisms in crushing that are to be included in the material model formulation;
2. The extraction of relevant material properties for crash from experiments;
3. The development of crush tests which can be simulated relatively easily in order to support the development and validation of the FE codes.

The numerical efforts include (i) the development of a physically-based ply model for crash, and (ii) the improvements of the computational efficiency of crash simulations. Those research topics are being addressed as part of the project "Modelling crash behaviour in future lightweight composite vehicles – step 1" [27], which is carried out in a strong interaction with the research presented in this thesis.

(i) Development of a physically-based ply model for crash

A physically-based ply model for crushing of composites consists of an elastic model, a set of failure criteria, and a post-failure damage model. State of the art physically-based failure criteria are predictive for failure initiation in UD plies with prepreg reinforcements [28]. Additional failure modes are observed experimentally in composites with textile reinforcements and need to be incorporated into a new set of failure criteria [29].

The model must capture the progression of damage accurately because it accounts for a great amount of energy absorbed during crushing. The continuum damage mechanics (CDM) approach has been used to predict damage propagation after failure initiation [30, 31]. Post-failure CDM damage models rely on the formulation of a damage variable that allows certain stress components to be degraded, thus capturing the stiffness degradation of the damaged material.

(ii) Improvements of the computational efficiency of FE simulations

Physically-based ply material models rely on precise 3D stress evaluation in order to accurately capture the complexity of the failure mechanisms of a composite ply. In a FE scheme, this means that the mesh of the structure should be sufficiently fine and that the element formulation should be able to predict the variation of stresses in the through-the-thickness direction. This can easily make the crash analysis extremely computationally costly and discourage industry to use the models.

Besides failure at the ply level, crash simulations should also accurately capture interlaminar failure responsible of splaying. The cohesive zone approach is predictive of interlaminar failure initiation and propagation. However, it requires the insertion of elements at every single interface of the laminates, which increases the complexity and computation time of FE simulations. Attempts to address these issues have been provided by Främby [32].

3 Material characterisation for crash simulation of composites

3.1 NCF composites – a candidate for composite cars

NCF are textile reinforcements made of one or several layers of parallel fibre tows (or bundles) stacked on top of each other and held together with a binding yarn (or thread). If the fabric only contains one layer of parallel tows woven together with thin weft yarns, the reinforcement is denoted as uni-weave NCF. A comparison of the ply architecture of a composite reinforced with a UD prepreg tape and a composite reinforced with uni-weave NCF is given in Fig. 6. In prepreg composites it can be assumed that the fibres are straight and uniformly distributed transverse to the fibres (in the 2–3 plane). In contrast, the fibres in an NCF composite, as for any textile composite, exhibit waviness in the through-the-thickness direction (3–direction).

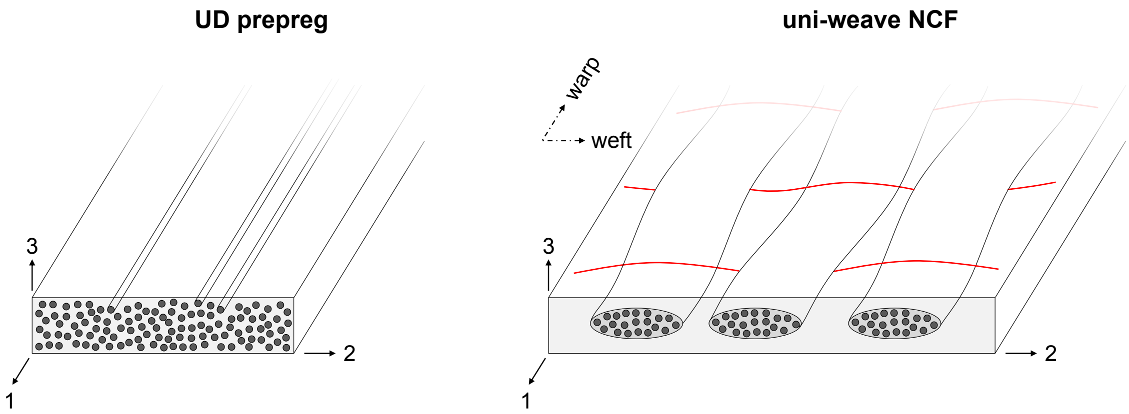

Figure 6: Illustration of a UD prepreg ply and a uni-weave NCF ply with weft threads.

The degree of waviness (or crimp) in NCFs is low in comparison to other textile reinforcements, thanks to the large difference in aspect ratio between the binding yarns and the bundles. Crimp ultimately results in a loss of in-plane mechanical properties compared to prepreg systems. In many applications, the benefit of textile reinforcements in terms of material costs, manufacturing procedures, and design possibilities can greatly justify the loss in mechanical properties. This loss is actually relatively moderate if NCF is selected for the textile reinforcement type [33]. This makes NCF composites a strong candidate for future lightweight road vehicles.

Unlike UD prepreg systems, NCF systems are not homogeneous at the ply level. The presence of fibre bundles, binding yarns and resin rich pockets makes the material orthotropic. This means that the properties must be defined along three mutually perpendicular directions: the fibre direction (1–direction), the in-plane transverse direction (2–direction), and the through-the-thickness direction (3–direction). Plies reinforced with UD prepreg tend to have equal properties in the 2–3 plane. They are approximated as transversely isotropic perpendicular to the fibres.

The mechanical characterisation of orthotropic materials is more demanding than of transversely isotropic materials. Dedicated through-the-thickness tests are necessary for orthotropic materials for a correct material description. An overview of available test methods for the determination of through-the-thickness strengths and stiffnesses of composites was given by Olsson [34].

The composite system investigated in Paper A, Paper B and Paper C is an epoxy resin reinforced with a uni-weave carbon fibre NCF.

3.2 Extraction of stiffnesses, strengths and fracture toughness properties – Paper A

It is well known that continuous FRPs cannot be regarded as isotropic materials (identical properties in all directions). They also behave differently in tension and compression. As a result, more mechanical tests are needed in comparison to characterisation of metals. Similarly, while the fracture toughness (material resistance to crack growth) of a metal is characterised by one single value, one fracture toughness for each existing failure mode must be defined for composite materials. This makes the full characterisation of the mechanical and fracture properties of composites a time-consuming and costly task in terms of testing.

In Paper A, a complete mechanical characterisation of the material selected for the research is performed. Rarely have the mechanical and fracture properties of a composite material system been evaluated thoroughly and shared with the scientific community. The lack of access to material data acts as a hindrance to research. It is not uncommon that researchers and engineers are assuming material data in their analytical or FE models because the required input are not available in the literature.

The tests performed for the material characterisation are shown in Fig. 7. Both standard tests and non-standard tests are needed to extract the different stifnesses and strengths of the ply, and the fracture toughness related to interlaminar and translaminar failure modes. The non-standard tests (through-the-thickness tension/compression [35] and translaminar fracture toughness [36]) are not necessarily well known by the industry. By publishing Paper A in an open access journal, the article can reach a larger potential audience and provide guidelines for the characterisation of any continuous FRP to many industries.

In the results presented in Paper A, it was found that the weft thread of the NCF has a significant effect on the strength. When loading the resin in tension the failure initiates from the weft thread inclusions in the UD laminate. As a result, a relatively low in-plane transverse strength was measured compared to similar carbon/epoxy FRP systems. The stress concentration generated from the weft threads, and the interface properties between the thread and the resin of the composite are things to consider when studying failure of NCF reinforced composites. The effect of the NCF mesostructure was also found to have an influence in the case of crushing, as reported in Paper C.

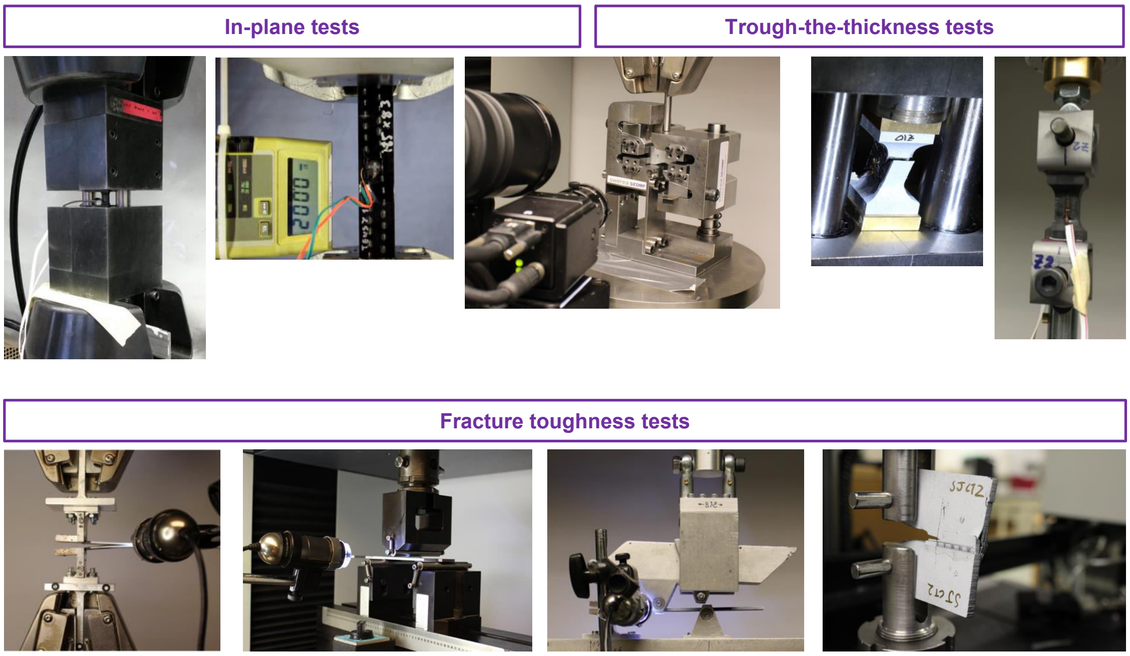

Figure 7: Test methods for the extraction of in-plane and through-the-thickness mechanical properties and fracture toughness properties.

3.3 Constitutive response and damage growth in shear – Paper B

The characterisation of shear behaviour is one of the most challenging areas of the mechanical testing of composite materials. There has been a much greater variety of shear test methods for composite materials developed during the last 40 years than for tension and compression tests [37]. The reason for this is the difficulty in achieving a pure and uniform shear stress state in the specimen, which is a requirement for an accurate evaluation of the shear properties.

In Paper B, the quality of the Iosipescu shear specimen is assessed experimentally with a full-field strain measurement technique and numerically with an FE analysis. The results show the validity of the Iosipescu test method for uni-weave NCF composites.

The shear response of FRP is strongly nonlinear. A possible explanation is the onset of microcracks in the resin before final failure. Those cracks are precursors of shear hackles, which are features often observed on the fracture surfaces of semi-brittle matrix composites [38]. Cyclic tests are needed to quantify the nonlinear shear behaviour in terms of stiffness degradation and accumulation of permanent strains. In Paper B, the shear stress–strain curves obtained from cyclic tests are used to calibrate available material models incorporating damage [30, 39], as illustrated in Fig. 8. It was found that the dissipation of energy is greater in the CDM based material model accounting for friction on microcracks [39]. This strengthens the argument of that frictional effects must be captured accurately to predict energy absorption during progressive failure.

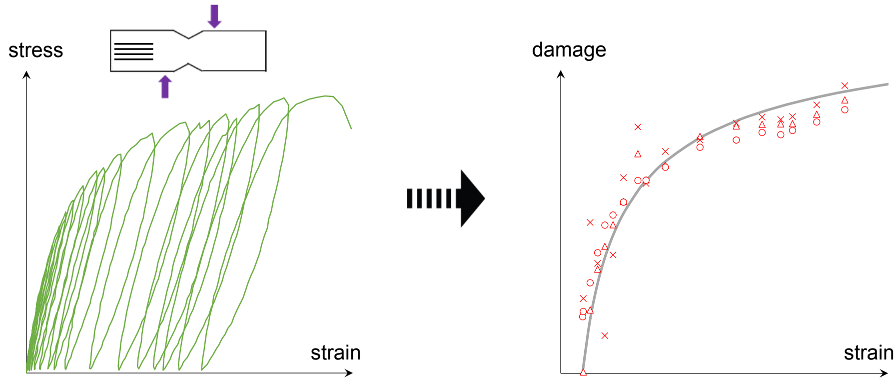

Figure 8: Left: Shear response obtained experimentally from cyclic Iosipescu shear tests. Right: Damage evolution curves obtained experimentally and calibrated to a material model.

Because of the orthotropic nature of NCF plies, the shear response in the 1–3 material plane (through-the-thickness shear) differs from the shear response in the 1–2 material plane (in-plane shear). The extraction of the through-the-thickness shear response of fibre reinforced polymers requires the manufacturing of relatively thick test specimens [34, 37]. The dimensions of the Iosipescu specimen are small enough for a thick laminate to be manufactured with a standard composite manufacturing technique, so the 1–3 shear behaviour was also evaluated in Paper B. The main finding of the study was that the failure in through-the-thickness shear tests was interlaminar and caused by the weft threads of the fabric. Therefore, and similarly to the observations made from tensile tests transverse to the fibres in Paper A, the through-the-thickness strength was lower than the in-plane strength.

3.4 Evaluation of crushing behaviour of a UD laminate – Paper C

Laminated tubes, corrugated plates, or more complex structures have been extensively used to investigate the specific energy absorption of a given material/structure system [9–16, 18–20]. Those tests capture the entire complexity of the crushing process, which makes it difficult to interpret the morphology of the crush front and to use the results for the development of ply damage models. However, those tests are good candidates for the validation procedure of mature numerical codes in a later stage of research.

The contribution of Paper C is concerned with the development of a simple test setup to extract the crushing response of UD laminates. The crush test is illustrated in Fig. 9. The specimens are flat coupons of small dimensions and the specimen fixture is kept simple as it only aims is to provide lateral support to the specimen. This test method was found to be sufficient to achieve progressive failure by crushing in the unsupported part of the specimen.

The longitudinal crushing mode could be controlled by an appropriate choice of

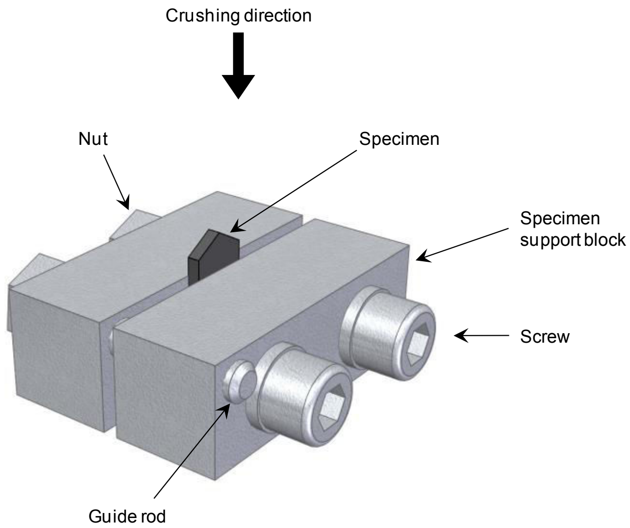

Figure 9: Illustration of the experimental test setup.

trigger. When using a bevel trigger, which is the most common type of trigger for composite tubes, the crushing mode of specimens loaded along the fibre direction was mostly splaying. In contrast, when the trigger shown in Fig. 9 was used, the out-of-plane failure and splitting failure were limited so fragmentation of the 0°-plies was achieved. Optical microscopy of the crush fronts of the specimens showed that the failure mechanisms involved in fragmentation are more energy efficient than those driving the splaying failure mode of the laminate. The crushing stress of a longitudinal ply failing by fragmentation is an important input to FE ply models for crash. This stress cannot be extracted directly from the crushing of tubes or corrugated specimens with a multidirectional lay-up or when splaying occurs in UD laminates.

It was also found that the mesostructure of the NCF laminate had a direct influence on the crushing response of longitudinal specimens. The clustering of NCF weft threads acts as delamination initiation sites and promote splaying failure. The weft threads did not influence the crushing response of the specimens loaded in the direction transverse to the fibres, neither did the trigger geometry.

4 Conclusions and outlook

The goal of reliable numerical predictions of the crashworthiness of composite structures cannot be achieved without combined experimental and numerical efforts. Mechanical tests on UD laminates, including non conventional through-the-thickness tests, is the first step to take in the characterisation of a textile reinforced composite material. It provides the different stifnesses, strengths, and information on failure morphologies of a ply to be used for failure initiation criteria for example.

The fracture toughnesses associated with different failure modes are important parameters to model the post-failure response, but other input are also needed to physically-based ply damage models. In particular, the nonlinear behaviour of the shear response of FRP can be used to calibrate material models incorporating damage growth. Information on the energy dissipation during damage growth may be extracted from cyclic stress–strain curves obtained from Iosipescu tests. Given the important role of matrix shearing in the different compressive failure modes of composite plies, an accurate measurement of the constitutive shear response of the material is needed. A numerical and experimental stress/strain analysis of Iosipescu specimens was performed for this purpose.

A test method was developed to extract the crushing stress of a ply while minimising the out-of-plane failure modes. The longitudinal and transverse crushing stresses were evaluated from the tests to provide input to ply material models for crash.

4.1 Missing input to finite element models

The crashworthiness of composite structures is usually measured from quasi-static crush tests. From the literature, there is still no agreement on how much the energy absorption capability is influenced by dynamic conditions [7]. If the crushing process for a given material system differs from quasi-static conditions to dynamic conditions, the strain rate effects must be investigated and accounted for in the FE models for crash.

The shear response of FRP in the 2–3 material plane is difficult to measure experimentally. The material is brittle in this plane and fails in tension when subjected to a pure shear stress state (failure occurs in a plane perpendicular to the principal stress direction). Instead of a pure 2–3 shear response, the input to material models may consist of the stress–strain curve of a test performed under a controlled state of combined normal loading and shear loading.

A great amount of energy absorbed during crushing comes from frictional effects. However, only little data has been published for the coefficient of friction between two composite surfaces [40] and more research is needed to be able to accurately predict the energy absorbed by friction during crushing and delamination growth.

The crush tests performed on 0°–specimens in Paper C could be extended to off-axis specimens to validate physically-based material models for longitudinal compressive failure of a ply, while the crushing response of multidirectional laminates could be used as validation tests for FE simulations with a ply material model and an interlaminar model for progressive damage.

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